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A strongly s-process enriched RV Tauri star in the LMC*

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Abstract. A detailed abundance analysis is presented of an intriguing object in the Large Magellanic Cloud that links the class of RV Tauri stars to the post-AGB phase of evolution: MACHO 47.2496.8. The spectrum, taken with VLT-UVES, is dominated by molecular lines of carbon bearing molecules, together with strong transitions of s-process species. Detailed spectral syntheses were made using a state-of-the-art carbon rich MARCS model. A surprisingly low metallicity ([Fe/H] = −1.4), together with strong carbon (C/O>2) and s-process overabundances were found, reaching values of [ls/Fe] = +1.2 for the light s-process elements, and even [hs/Fe] = +2.1 for the heavy ones. The strong s-process enhancements are in agreement with the theoretical expectations at that metallicity. Only the combination of a low lead content and a high [hs/ls] is not easily explained by the current nucleosynthetic models. It is not clear whether this star is intrisically or extrinsically enriched, but several arguments favour an intrisic enrichment, implying the object to be a genuine post carbon (N-type) AGB star. With the low metallicity and a luminosity at the very low end of the carbon star luminosity function, MACHO 47.2496.8 represents the final evolutionary state of a star of low initial mass.

Key words. Stars: AGB and post-AGB – Stars: abundances – Stars: carbon – Stars: individual: MACHO 47.2496.8 – Magellanic Clouds

1. Introduction

RV Tauri stars are a heterogeneous subclass of the Pop. II Cepheids, showing alternating deep and shallow minima in their light curves, with periods between 30 and 150 days. Since IRAS, we know that many of these stars show infrared excesses caused by circumstellar dust, and hence they are believed to be post-AGB stars. Clear *chemical* evidences (like carbon and s-process enrichment) that RV Tauri are post-AGB stars were never found. Only two RV Tau stars show a mild enhancement in s-process el-

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* based on observations collected at ESO, Chile (programme 074.D-0619(A))

** Postdoctoral fellow of the Fund for Scientific Research, Flanders ements: V453 Oph (Deroo et al. 2005) and V1 in ω Cen (Wallerstein & Cox 1984). Both stars don't show, however, a standard AGB nucleosynthetic pattern after efficient 3rd dredge-up. Instead, many RV Tauri stars show some degree of *depletion* in their photospheres, which is caused by a gas-dust separation in the circumstellar environment and a subsequent gas accretion, making the photosphere devoid of refractory elements. A depletion pattern is easily recognised by a high [Zn/Fe] ratio, since Zn has a much lower condensation temperature than iron (see review by Van Winckel 2003).

The luminosities of field RV Tauri stars are difficult to assess, since no distances are known. The genuine high luminosity of RV Tauri stars was, however, confirmed by the detection of RV Tauri candidates in globular clusters and in the LMC. The MACHO experiment, an intensive monitoring with a dedicated 1.27 m telescope on Mt. Stromlo of mainly the LMC during several years, found several tens of Pop. II Cepheids in the LMC, including ~10 new RV Tauri stars (Alcock et al. 1998). The high-resolution spectrographs on 8m class telescopes, make it now possible to study in detail the abundance patterns of these individual RV Tauri candidates. In this contribution, we report our results of the brightest object of the Alcock et al. (1998) sample, MACHO 47.2496.8. Pollard & Lloyd Evans (2000) discussed a series of low-resolution spectra of this object taken at different pulsational phases. The low-resolution spectra showed very strong C_2 bands at minimum light, which almost completely disappeared in more luminous phases. Moreover, a strong enhancement of the Ba II features was seen, indicating that MACHO 47.2496.8 is probably the first RV Tauri star that is carbon and s-process enriched. Here, we present an overview of the first abundance analysis of this unique object, which will be presented in full detail in an upcoming paper (Reyniers et al. 2006).

2. Observations

High-resolution, high signal-to-noise optical spectra of our programme star were taken with the UVES spectrograph on the VLT-UT2 (Kueyen) telescope. Two instrument settings were used, so that the complete optical domain was sampled, from 376 nm to 1008 nm, at a resolving power of ~60000. The integration time was two hours in each setting. The reduction was performed in the "UVES-context" of the MIDAS environment, and included all standard procedures required in echelle reduction. Optimal extraction was used to convert the echelle data from pixel-pixel to pixel-order space. The signal-to-noise (S/N) ratio depends on wavelength, being lower in the blue wavelength range. Exact values for the S/N ratio of the final reduced data-product are difficult to determine, since the spectrum is so crowded that a continuum interval long enough to estimate the S/N ratio, was not found in the spectrum. Conservative estimates for the S/N ratios are ~40 for the blue region and ~80 for the red region. Sample spectra can be found in Figs. 1, 2 and 3.

3. Analysis

3.1. Description of the spectra

The high-resolution spectra are mainly characterised by (1) strong bands of carbon bearing molecules and (2) atomic transitions of s-process elements. Particularly the molecular lines of C_2 are very strong, and the band heads are saturated (see e.g. Fig. 1). Also the CN bands are quite strong, although less pronounced than C_2. Since the bands are so strong, the spectrum of MACHO 47.2496.8 mimics the spectrum of a cool carbon star. The strong atomic features of s-process elements clearly point to a higher temperature than a typical carbon star temperature. Also the clear presence of the Balmer Hα and Hβ points in that direction. Deriving the appropriate atmospheric parameters was one of the main difficulties in the analysis of MACHO 47.2496.8.

3.2. Model atmospheres and atmospheric parameters

Before we started the actual analysis, we performed a thorough study of the atmospheric parameters of our programme star, by using a newly calculated grid of cool carbon-rich MARCS model atmospheres. The details of these models will be given elsewhere (Gustafsson 2006; Jørgensen 2006). The derivation of the model parameters is not easy, since the molecular veiling is very strong in most spectral regions. We inferred the parameters by an iterative process of fitting specific spectral regions and consequently adapting the model parameters, until a satisfactory fit was obtained between observed and synthetic spectrum. Since the model parameters are not independent, this procedure is not straightforward. Moreover, different sets of parameters can produce a very similar synthetic spectrum. This is particularly the case for the carbon-oxygen content: adding simultaneously the same amount ($\lesssim 0.2$ dex) of carbon and oxygen to the atmosphere, will only slightly influence the spectrum, since the added carbon and oxygen will immediately coagulate in the strongly bound CO molecule. The final atmospheric parameters obtained from the fitting iteration were additionally tested by two independent methods: Balmer line fitting and the study of some clean iron lines. Both tests confirmed the final parameters: $T_{\rm eff} = 4900$ K, $\log g = 0.0$, $\xi_t = 3$ km s^{-1} and model metallicity [M/H] $= -1.5$.

3.3. Abundance analysis

Since the spectrum of MACHO 47.2496.8 resembles the spectrum of a cool carbon (N-type) star, we concentrated our spectrum syntheses on the regions that are also normally used in this type of stars (Abia et al. 2002; de Laverny et al. 2006). Atomic line lists are taken from the Vienna Atomic Line Database (VALD), completed with lines from DREAM for the lanthanides. Molecular line lists are compiled from different sources, and are discussed in de Laverny et al. (2006). For a detailed report of our analysis, we refer to our upcoming paper (Reyniers et al. 2006). Here we briefly discuss our main results, graphically presented in Fig. 4. Note that errors are not easy to quantify given the wide variety of error sources (continuum placement, atmospheric parameters, $\log gf$ values, undetected blends, etc...).

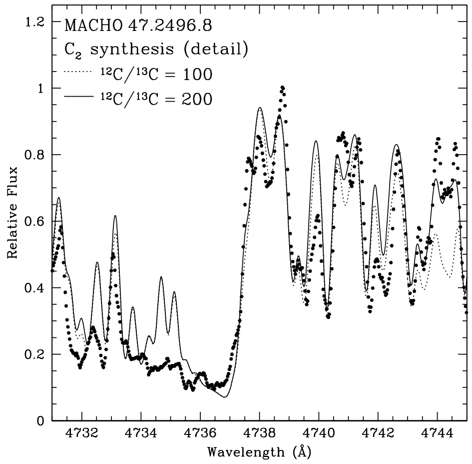

Fig. 1. Spectral synthesis of the 4737 Å C_2 band head region, with two different $^{12}C/^{13}C$ ratios. The observed spectrum is plotted with dots.

The CNO abundances are difficult to determine in this temperature-gravity domain and only some uncertain estimates can be made. The C/O ratio is high, and definitely larger than 2. For the N abundance, only an upper limit can be derived, being $\log \epsilon(N) < 7.45$. The $^{12}C/^{13}C$ ratio is determined from the band head at 4737 Å (Fig. 1), and confirmed by the synthesis of CN features at 8000 Å: $^{12}C/^{13}C = 200 \pm 25$.

The abundances of the α-elements show a somewhat confusing pattern, with a relatively high Mg content, combined with a low Ca abundance. We do not have an obvious explanation for this significant abundance difference, although it is well known that the lighter α-elements are mainly produced inside massive stars, while the heavier α-elements are formed during explosive nucleosynthesis.

The iron content is surprisingly low for a field LMC star, being [Fe/H] $= -1.4$. The other iron peak elements Ni and Zn do follow this deficiency, so that there is no indication for depletion.

The dominance of transitions of s-process elements is striking from Fig. 2. In this fig-

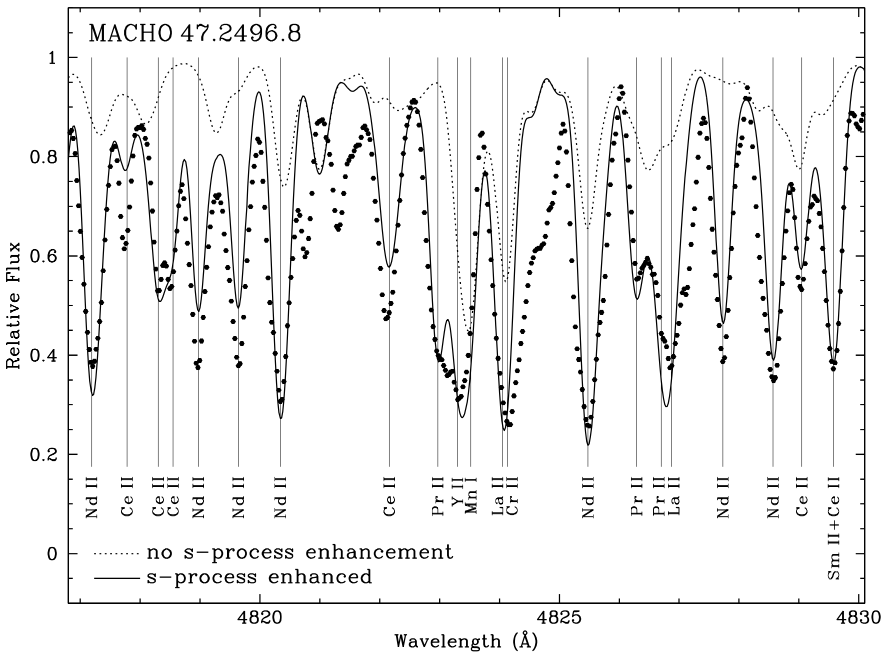

Fig. 2. The observed spectrum of MACHO 47.2496.8 (dots), overplotted with two spectral syntheses, one with solar s-process abundances (scaled down to the metallicity of MACHO 47.2496.8), and one with the final s-process abundances.

ure, a synthesis is performed *with* and *without* s-process enhancement. It is clear that the spectrum is shaped by the s-process atoms, especially lines of Ce II and Nd II. Abundances were derived for both the light s-process elements (ls) of the strontium peak Y and Zr, and the heavy s-process elements (hs) of the barium peak La, Ce, Pr, Nd and Sm. As can be seen from Fig. 4, the overabundances are high, being [ls/Fe] = +1.2 and [hs/Fe] = +2.1. The [hs/ls] ratio, which is an observational index to characterise the s-process efficiency is hence [hs/ls] = +0.9. Concerning the s-process elements beyond the barium peak, we found one weak line of hafnium (Hf), resulting in (a rather uncertain) [Hf/Fe] = +2.0. We also synthesized the Pb line at 4057.8 Å, but the uncertain continuum placement in this region makes the derivation of a Pb abundance impossible. We could only derive an upper limit of [Pb/Fe] $\lesssim$ 2.1, as illustrated in Fig. 3.

The synthesis of the 6707.8 Å region did not show an enhanced lithium content, and resulted in an upper limit of $\log \epsilon(\mathrm{Li}) < 1.5$.

4. Discussion

4.1. Intrinsic or extrinsic?

No galactic RV Tauri stars are known that undoubtfully show *chemical* evidence for their supposed evolutionary status of post-AGB stars. By displaying clear carbon and very strong s-process overabundances, MACHO 47.2496.8 is the first object that chemically links the RV Tauri class of objects with the s-process enriched (post-)AGB stars. Another possibility is, of course, that the star is extrinsically enriched by mass transfer from a former AGB companion. Extrinsically enriched giants of low metallicity do exist in the galaxy, and are labeled as the CH-stars, the

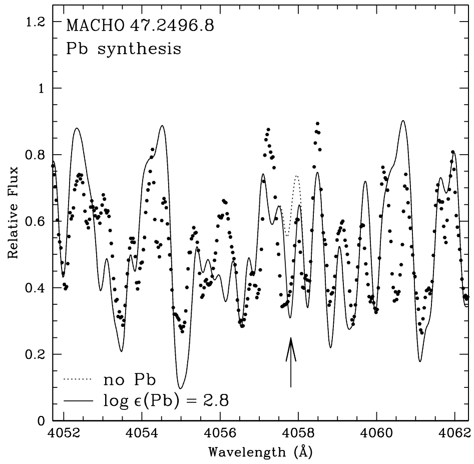

Fig. 3. Synthesis of the Pb I line at 4057.81 Å, together with the observed spectrum (dots). From the figure it is clear that the continuum placement is the main source of uncertainty in this region.

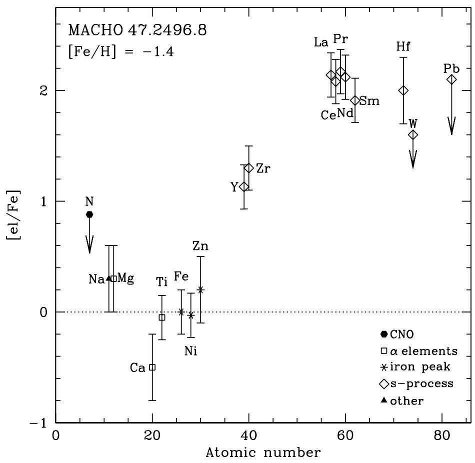

Fig. 4. The final abundances of MACHO 47.2496.8, relative to iron [el/Fe].

Pop. II analogues of Ba-stars, but they are rare (Ba-stars represent only 1% of the G-K giants, Jorissen 2003).

The classical indicator whether a star has suffered either an intrinsic or an extrinsic enrichment, is the presence of technetium in the photosphere, since Tc has a half-life of $\sim 2\times 10^5$ yr. The synthesis of the Tc line at 4262 Å did not give any clue on its presence or absence, since the line itself is intrinsically very weak, and the blending is too severe to make any conclusion. Niobium (Nb) is an alternative indicator for the intrinsic/extrinsic enrichment since the only stable isotope is ^{93}Nb is formed by the decay of ^{93}Zr, which has a half-life of 1.5×10^6 yr. Hence, only in *extrinsic* stars, ^{93}Zr had the time to decay to Nb and reaching [Nb/Zr]~0. Unfortunately, also for Nb, we did not find any line suitable for abundance determination purposes.

The luminosity of MACHO 47.2496.8 (mean visual magnitude of $M_V \simeq -3.9$ from Alcock et al. 1998,$M_{bol} \simeq -4.2$) is more compatible with an advanced stage of a low mass star, than with a CH star-like luminosity. The low metallicity is corroborating the likely low initial mass of the object. However, a very low initial mass is somehow in conflict with the strong s-process enhancement: very low mass stars are not expected to suffer 3rd dredge-up (e.g. Straniero et al. 2003). This qualitative statement is confirmed by comparing the inferred bolometric magnitude of MACHO 47.2496.8 with the Carbon Star Luminosity Function (CSLF) for the LMC (e.g. Groenewegen 2004). It is well known that the low luminosity end of the observational CSLF cannot be explained adequately with the present AGB nucleosynthetic models. The low luminosity tail is, however, recently successfully fitted with a population of extrinsically enriched giant stars by Izzard & Tout (2004). The transition between the extrinsic, low luminosity carbon stars, and the genuine C(N-type) AGB stars is situated around $M_{bol}\sim -4$, exactly the luminosity of MACHO 47.2496.8. The bolometric correction might be, however, not very accurate: for genuine carbon stars, the bolometric luminosity is in many cases ~1 magn. brighter than the one inferred by the current calibrations (Guandalini et al. 2006).

4.2. The lead content

Another remarkable result that should be discussed is the Pb content. Several nucleosynthetic models, like Gallino et al. (1998) and Goriely & Mowlavi (2000), predicted that the s-process nucleosynthesis in a low metallicity star would easily reach its end-point, and produce large amounts of lead. A careful reanalysis of the CH-giants confirmed the existence of such "Pb stars", as was first discovered by Van Eck et al. (2001). Subsequent analyses (Aoki et al. 2001, 2002; Van Eck et al. 2003) found more of these lead stars, but it was also realised that s-process enhanced stars exist *without* the predicted Pb overabundance. A low Pb content in combination with a strong s-process enrichment, is not easily explained by the current AGB nucleosynthesis models. For MACHO 47.2496.8, [Pb/hs] $\lesssim 0$, and therefore joins this group of stars with an unexpectedly low lead abundance.

5. Summary

MACHO 47.2496.8 is an RV Tauri star in the LMC, discovered by the MACHO experiment (Alcock et al. 1998). Low resolution spectra showed strong C_2 bands and strong Ba II lines, suggesting that this RV Tauri star could serve as the link between the RV Tauri stars and the (post-)carbon (N-type) stars. In this contribution, we presented a detailed abundance analysis of this source, based on high-resolution, high signal-to-noise VLT spectra, and using state-of-the-art carbon-rich MARCS model atmospheres. The main results are summarised as follows: (1) a surprisingly low metallicity: [Fe/H] = −1.4, with no evidence of depletion; (2) a high C/O ratio, certainly larger than 2, and a $^{12}C/^{13}C$ ratio of ~200; (3) a huge s-process enrichment with [ls/Fe] = +1.2 [hs/Fe] = +2.1; (4) a low Pb abundance [Pb/Fe] $\lesssim$ [hs/Fe]; and (5) a luminosity at the very faint limit of the carbon star luminosity function.

While it is not a priori clear whether this object is either intrinsically or extrinsically enriched, the most favourable possibility is that the star is a genuine post carbon (N-type) AGB star. The huge s-process enrichment is predicted by the nucleosynthetic models for this metallicity, but the low lead content is not, and should be further explored in the models. Also, the metallicity itself is surprisingly low for a field LMC star. All these characteristics make MACHO 47.2496.8 a highly intriguing object.

References

Abia, C., Domínguez, I., Gallino, R., et al. 2002, ApJ, 579, 817
Alcock, C., Allsman, R. A., Alves, D. R., et al. 1998, AJ, 115, 1921
Aoki, W., Ryan, S. G., Norris, J. E., et al. 2001, ApJ, 561, 346
Aoki, W., Ryan, S. G., Norris, J. E., et al. 2002, ApJ, 580, 1149
de Laverny, P., Abia, C., Domínguez, I., et al. 2006, A&A, 446, 1107
Deroo, P., Reyniers, M., Van Winckel, H., Goriely, S., & Siess, L. 2005, A&A, 438, 987
Gallino, R., Arlandini, C., Busso, M., et al. 1998, ApJ, 497, 388
Goriely, S. & Mowlavi, N. 2000, A&A, 362, 599
Groenewegen, M. 2004, astro-ph/0407282
Guandalini, R., Busso, M., Ciprini, S., Silvestro, G., & Persi, P. 2006, A&A, 445, 1069
Gustafsson, B., et al., 2006, A&A, in preparation
Izzard, R. G. & Tout, C. A. 2004, MNRAS, 350, L1
Jørgensen, U.G., et al., 2006, A&A, in preparation
Jorissen, A. 2003, in "Asymptotic Giant Branch Star", edited by Habing H. and Olofsson H. (Springer-Verlag), 461–518
Pollard, K. R. & Lloyd Evans, T. 2000, AJ, 120, 3098
Reyniers, M., Abia, C., Van Winckel, H., et al. 2006, A&A, in preparation
Straniero, O., Domínguez, I., Cristallo, R., & Gallino, R. 2003, PASA, 20, 389
Van Eck, S., Goriely, S., Jorissen, A., & Plez, B. 2001, Nature, 412, 793
Van Eck, S., Goriely, S., Jorissen, A., & Plez, B. 2003, A&A, 404, 291
Van Winckel, H. 2003, ARA&A, 41, 391
Wallerstein, G. & Cox, A. N. 1984, PASP, 96, 677